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6. AUTHOR(S)

Daniel L. Noneaker

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Clemson University
300 Brackett Hall
Box 345702
Clemson, SC 29634-5702

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
ATTN: AMSRL-R0-S (TR)
P.O. Box 12211
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12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. ABSTRACT (Maximum 200 words)

Research is conducted on techniques for acquisition of direct-sequence spread-spectrum packet transmissions with radios using omnidirectional or switched, sectorized antennas in distributed packet radio networks. Both serial and hybrid algorithms for noncoherent acquisition are considered. Research is also conducted on the development of channel-access protocols for nodes employing sectored or switched-beam antennas. The protocols are designed to account for co-site interference in modes with multiple beams. The protocols are shown to provide robust network operation with an arbitrary heterogeneous mix of node capabilities.

Research is also conducted on routing protocols for communications in microsensor networks. Novel routing metrics are developed that account for the remaining battery energy in each node as well as the rate at which each node is depleting its remaining energy. The effect of jamming on the lifetime of sensor networks is investigated, and algorithms for lifetime-prolonging node hibernation are developed.

14. SUBJECT TERMS	15. NUMBER OF PAGES
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Project Description

I. Statement of problem studied

Spread-spectrum packet radio networks with fully distributed network control are uniquely well suited to support tactical communications in ground-combat operations. Most current technologies and current research for fully distributed packet radio networks are centered around the concept of a network of peer radios of equal capabilities. Much of the research has been focused implicitly on networks of manpack radios that use omnidirectional antennas. It is likely that future tactical packet radio networks will be required to incorporate radio systems with a wide range of capabilities, however. Microsensors of very limited energy-storage capacity will be employed in the battlefield in large numbers. Critical sensor summary data can be transmitted to data-fusion centers or to the soldier in the field with greater reliability if the microsensors can utilize the mobile elements of the tactical packet radio network in order to relay the sensor data. At the same time, some vehicle-mounted radio systems will have a power supply and platform that can support an adaptive array of antennas. The throughput of the network can be increased dramatically if the network protocols are designed to exploit opportunistically the presence of mobile radios with adaptive arrays.

This research project has focused on the development of protocols and reception techniques for distributed packet radio networks that exploit directional antennas to provide high-throughput, reliable data and voice communications and that conserve sensor battery energy when relaying sensor data through the network. The research has focused on the development of channel-access protocols, adaptive link protocols, and adaptive routing protocols for packet radio networks that employ spread-spectrum modulation. One goal of the research has been to ensure that critical data is forwarded from microsensors to data-fusion centers or mobile-radio end systems while efficiently utilizing the limited energy in the sensors' nonrechargeable batteries. A primary research emphasis has been the design of protocols that minimize the total energy consumption for store-and-forward routing through the subnetwork of microsensors and that account for energy depletion in individual sensors. An important component of this emphasis is the design of protocols that utilize more-capable radio systems in the tactical network whenever possible in order to minimize the amount of data relaying required of the sensors. A second, related emphasis has been efficient exploiation of the presence within the tactical network of mobile radio systems that utilize directional antennas. Primary topics of the research include the design of the packet-acquisition techniques, channel-access protocols, and resource-managment techniques that allow a node with multiple fixed-beam directional antennas to exploit their capabilities without introducing a significant increase in the complexity of the network's protocols.

II. Summary of most important results

We have completed the investigation of a serial acquisition algorithm which employs an estimator to adaptively select the acquisition threshold on a sample-by-sample basis. The estimator is a windowed linear filter applied to the recent past samples out of the matched filter

of the acquisition stage. It is shown that the filter output is an unbiased estimate of the mean sample value if only noise is present, and it has a small negative bias is a signal is present. It is also shown that the technique reduces the severity of the non-monotonicity, and indeed it achieves a nearly constant false-alarm rate over an arbitrary range of (unknown a priori) signal-to-noise ratios. The technique substantially improves the acquisition performance in comparison with both the fixed-threshold technique and the first adaptive-threshold technique. It is also shown that the second adaptive-threshold technique results in a substantial reduction in the sensitivity of the performance to variations from the nominal bandwidth of the IF noise-rejection filter, and it eliminates sensitivity to variations of the AGC's steady-state output voltage from its nominal value. We have examined the second adaptive-threshold technique for both serial and hybrid serial/parallel algorithm for acquisition of DS packet transmissions. It is shown that the techniques works well with both algorithms, and the hybrid algorithm results in better performance than noncoherent serial acquisition.

We have developed and evaluated the performance of a multichannel RTS-CTS-based channel-access protocol in an ad-hoc network that contains an arbitrary mix of nodes with multiple direcional antennas and nodes with omnidirectional antennas. We demonstrate a counter-intuitive phenomenon that occurs due to differences in channel-state information between the transmiting node and the receiving node. The phenomenon can result in poorer network performance in some circumstances if some of the nodes use multiple directional antennas than if all the nodes use omnidirectional antennas. We have shown that the phenomenon is a generalization of the *receiver blocking problem* that has been identified previously in ad hoc networks in which all the nodes have omnidirectional antennas. However, as we demonstrate, this phenomenon can have much greater impact on performance if the transmitting and receiving nodes have directional antennas. We examine in detail the mismatch in channel-state information that is the underlying reason for the misinformed problem. And we demonstrate a modification of the multi-channel RTS-CTS protocol that corrects this mismatch in channel-state information by exploiting the availability of the control channel. We show that this modified protocl substantially mitigates the receiver blocking problem, and it results in much better performance in a networks in which some of the nodes employ directional antennas.

Our research has also focused on the design of routing metrics for wireless microsensor networks that are specifically designed to operate well despite a moderate level of uncertainty in the amount of energy remaining in node batteries. Improved routing metrics have been developed that exploit statistical models for battery level uncertainty. The performance of these metrics has been investigated in networks with multiple data collection nodes, multiple transmitter power levels, and nonhomogeneous traffic. Results show that the metrics provide significant gains in network lifetime of metrics that ignore the effects of battery level uncertainty.

Additionally, the effects of jamming on the lifetime of sensor networks has also been investigated. The focus of this investigation has been on time-varying jamming and its effects on adaptive route selection. Results show that the use of frequent or aggressive route update algorithms can significantly degrade performance when an on-off jammer is present.

An topic of our research has been the development of node hibernation (sleep) algorithms

for sensor networks. Algorithms have been designed that have nodes query their neighbors to determine the potential effect of going off-line for an extended period of time. Such protocols have been shown to be capable of providing significant gains in network lifetime, especially in highly-connected, dense networks. Results include theoretical analysis and simulation of specific protocols.

III. List of publications and technical reports

Papers published in peer-reviewed journals

D. L. Noneaker, A. R. Raghavan, and C. W. Baum, "The Effect of Automatic Gain Control on Serial. Matched-Filter Acquisition in Direct-Sequence Packet Radio Communications," *IEEE Transactions on Vehicular Technology*, vol. 50, no. 4, pp. 1140-1150, July 2001.

Papers published in non-peer-reviewed journals or in conference proceedings

D. L. Noneaker, "Robust Hybrid Acquisition of DS Packet Transmissions," in *Proc. 2001 IEEE Int'l. Symp. Commun. Theory and Applications*, (Ambleside, UK), pp. 427–432, July 2001.

F. J. Block and C. W. Baum, "Energy-Efficient Self-Organizing Communications Protocols for Wireless Sensor Networks," in *Proc. 2001 IEEE Military Commun. Conf.*, (McLean, VA), pp.10.3.1-5, Oct. 2001.

D. L. Noneaker, "The Performance of Serial, Matched-Filter Acquisition in Direct-Sequence Packet Radio Communications," in *Proc. 2001 IEEE Military Commun. Conf.*, (McLean, VA), pp.31.6.1-5, Oct. 2001.

D. L. Noneaker and A. Swaminathan, "Acquisition Techniques for Packet Radio Communications," in *Proc. 40th Annual Allerton Conf. Commun., Contr., Comput.* (Monticello, IL), Oct. 2002.

F. W. Block and C. W. Baum, "An Energy-Efficient Routing Protocol for Wireless Sensor Networks withBattery-Level Uncertainty," in *Proc. 2002 IEEE Military Commun. Conf.* (Anaheim, CA), paper 448, Oct. 2002.

A. Swaminathan and D. L. Noneaker, "Performance of Serial, Matched-Filter Acquisition with Adaptive Thresholds in Direct-Sequence Packet Communications," in *Proc. 2002 IEEE Military Commun. Conf.* (Anaheim, CA), paper 184, Oct. 2002.

A. Swaminathan and D. L. Noneaker, "A Technique to Improve the Performance of Serial, Matched-Filter Acquisition in Direct-Sequence Spread-Spectrum Packet Radio Communications," in *Proceedings of the 2003 IEEE International Conference on Communications*, (Anchorage, AK), paper 184, May 2003.

F. J. Block and C. W. Baum, "Routing to preserve energy in ad hoc networks subject to jamming," to appear in *Proceeding of the 2004 IEEE Military Communications Conference*, (Monterey, CA), Nov. 2004.

A. M. Panchabhai and C. W. Baum, "Node hibernation protocols for conservation of energy

in wireless sensor networks," to appear in *Proceeding of the 2004 IEEE Military Communications Conference*, (Monterey, CA), Nov. 2004.

A. Swaminathan and D. L. Noneaker, "The Effect of Mismatch in Channel-State Information on a DS Mobile Ad Hoc Network with Directional Antennas," to appear in *Proceeding of the 2004 IEEE Military Communications Conference*, (Monterey, CA), Nov. 2004.

Papers presented at meetings, but not published in conference proceedings

D. L. Noneaker, "Medium-Access Control Protocols for Heterogeneous Mobile Ad Hoc Networks with Directional Antennas," presented at *NATO IST-030/RTG-012 Workshop on Cross-Layer Issues in the Design of Tactical Mobile Ad Hoc Wireless Networks*, Naval Research Laboratory, Washington, D.C. (June 2, 2004).

Manuscripts submitted, but not published

A. Swaminathan and D. L. Noneaker, "A Technique to Improve the Performance of Serial, Matched-Filter Acquisition in Direct-Sequence Spread-Spectrum Packet Radio Communications," submitted to the *IEEE Journal on Selected Areas in Communications, special issue on Advances in Military Wireless Communications.*

F. J. Block and C. W. Baum, "Routing in Wireless Networks with Battery-Level Uncertainty," submitted to the *IEEE Transactions on Wireless Communications.*

F. J. Block and C. W. Baum, "Routing to Preserve Energy in Ad Hoc Networks Subject ot Partial-Time Interference," submitted to the *IEEE Transactions on Wireless Communications.*

F. J. Block and C. W. Baum, "Information for Routing in Energy-Constrained Ad Hoc Networks," submitted to *Ad Hoc Networks* (an Elsevier Journal).

A. M. Panchabhai and C. W. Baum, "A hibernation protocol using multiple transmit power levels for wireless sensor networks," submitted to the 2004 IEEE GLOBECOM Symposium on Wireless Communications, Networks and Systems.

IV. List of participating scientific personnel

Daniel L. Noneaker, Associate Professor, Principal Investigator
Carl W. Baum, Associate Professor, Faculty Investigator

Fred J. Block, graduate student, earned Ph.D degree
Akhil M. Panchabhai, graduate student, earned M.S. degree
Arvind Swaminathan, graduate student, earned M.S. degree

Dwight Hutchenson, undergraduate student, earned B.S. degree
William McMahan, undergraduate student, earned B.S. degree

V. Report of Inventions

None.